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THE WAY TO INCREASED AIRPLANE ENGINE POWER

By Eugen Vohrer

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INTRODUCTION

The steadily increasing demands made on present-day power plants due to the continued development of the airplane raise more and more difficult design and production problems. Nevertheless, advances have been made in the development of the airplane engines such as would have been considered impossible a few years ago. Several engine manufacturers (Wright, Pratt & Whitney, and Bristol) were able in one decade to more than double the output of their engine types (Cyclone, Hornet, and Pegasus) for the same displacement volume and to reduce the weight/power ratio by almost half. How was this progress made possible?

The present-day high-power engines are the result of careful design making use of the laboriously won data on the application of higher speeds, greater mean and intake pressures, higher compression ratios and smaller fuel consumptions. A particular impulse was given by the use of higher knock-rating fuels and better lubrication oils, and the mechanical problems - reduced wear of the engine parts, increased useful life and improvement in over-all operating characteristics - are now solved to such an extent that the intervals between overhaulings have been lengthened from 250 hours to 500 to 600 hours and that the total life of the engine extended to more than 3,000 hours.

This rapid development in the airplane engine is responsible for the present-day flight performance. High short-period power performance reduces the take-off distance and makes possible favorable take-off characteristics also for high-speed aircraft. There is an increase in the rate of climb and at the higher altitudes high cruising speeds are attainable. The lowered fuel consumption results in considerably greater economy, pay load, and range, particularly for long-distance flights.

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*"Der Weg zum Hochleistungs-Flugmotor." Luftwissen, Bd. 5, Nr. 10, Berlin, October 1938, pp. 357-67.

Since 1934 there has been observed a strong increase in engine performance and, in almost every country with its own aviation industry, the center of interest is the large power unit capable of generating over 2,000 horsepower. Various papers have been published in recent times on the possibilities and problems arising in connection with the creation of suitable structural forms, cylinder size and arrangement, head resistance, cooling, etc. Our purpose in the present paper is to give an outline of the present state of development and point out the possibilities available for the further increase in the power/displacement ratio, the economy, and the reliability of the engine.

HIGH-OUTPUT ENGINES

In 1936, Nutt, chief designer of the Wright Aeronautical Corporation, denoted engines of 25 or more horsepower per liter as high-power engines. Today, after two years, we can already raise this number to about 30 horsepower per liter (0.41 hp./cu. in.) for engines of over 2 liters cylinder displacement and for the smaller cylinder dimensions to 35 horsepower per liter (0.57 hp./cu. in.). The present peak values (referred to power in take-off) for the large radial engines lie at 37 horsepower per liter (Wright Cyclone G 102, fig. 1), for the air-cooled in-line engines at 57 horsepower per liter (0.93 hp./cu. in.) Napier Dagger VIII, fig. 2), and for the liquid-cooled engine between 34 and 36 horsepower per liter (0.67 hp./cu. in.) (Rolls-Royce Merlin II, Allison V 1710-C6, fig. 3).

For the development of more than average-size airplanes there are available at present principally two types of engine construction; namely, the single-row, 9-cylinder, radial engine or the 14- and 18-cylinder, double-row, radial engine with 1,000 to 1,500 horsepower and the liquid-cooled, 2×6 cylinder, in-line, V engine with 1,000 horsepower output. In addition to the high-power, air-cooled, in-line H-type engine with 4×6 cylinders introduced in England some years ago, there has been an increase in the power of air-cooled, in-line, V engines (reference 1). The original problems of providing adequate cooling of the in-line engine have given rise to bold plans for the future with the object of developing engines that will be able to enter into serious competition with the liquid-cooled power plants.

Wood (reference 2) sees the trend of development of the liquid-cooled, in-line power plant in a 24-cylinder, X engine and points out that the engine and oil radiators could be built into the aircraft in such a manner that the total frontal cross section is only slightly greater than that of the engine alone. Actually for present-day aircraft with nozzle radiators, the power expenditure for cooling still amounts to about 5 to 10 percent of the engine power output (reference 3).

In the medium power outputs between 300 and 800 horsepower, the air-cooled, two-row engine predominates, followed by the single-row, radial engine, and only in individual cases is this performance given by the liquid-cooled engine. Engines of this output range of the air-cooled type at present attain power/displacement ratios of up to 38 horsepower/liter (Argus As 410, fig. 4; Renault 12 S) and the water-cooled type, 34 horsepower per liter (Jumo 210).

Since at large forward speeds the reduction of the frontal drag is often of greater effect than that of the weight, the large representation of the in-line engines in all power ranges is in no small measure due to their great success in the races of recent years and the victory of an air-cooled, in-line engine over the more than 50 percent stronger radial engines in the air races in the United States in 1936 (reference 1).

DEVELOPMENT OF PRESENT-DAY ENGINES

FOR HIGHER POWER OUTPUT

The continuous power developed by an engine determines in general the size of the swept volume. From the familiar power formula

$$N = \frac{1}{900} V_H \, n \, p_m$$

for equal displacement V_H, there are given the two possibilities of raising the power, namely, by application of higher rotational speeds (n), and by higher mean effective pressures (p_m). The maximum rotational speed of an engine is limited, however, by the restricted speed of the valve mechanism and by the maximum valve cross sections permitted by the cylinder head. For the engine with direct intake the maximum speed limit is characterized on the power diagram by the highest point on the power curve. More recent engines at standard conditions on a normal day attain at this point a mean indicated pressure of between 12 and 13 atmospheres (177 to 191 lb./sq. in.). Investigations have shown that this mean effective pressure can be attained for a gas speed at the inlet port of about 80 meters per second (262 ft./sec.) if the latter is computed from the ratio of piston area to the maximum free port area and mean piston speed (fig. 5). If the swept volume and size of port are held fixed, the maximum values of the speed and the power to be expected may be predicted from them. Since within wide limits the free inlet cross section determines the power developed by a cylinder further improvements in the flow relations, having regard to high rotational speeds and mean pressures, are particularly promising.

For the supercharged engine the increase in the size of the valve cross sections on account of the reduced flow losses in the ports means a lowering of the supercharge pressure, supercharge temperature, and supercharge power.

According to figure 6, the flow losses amount to about 45 percent of the total power losses. In the attempt further to reduce these throttle losses, there has been an increase, in the course of development, in the ratio of intake valve diameter/cylinder diameter to about 0.5 for the two-valve cylinder and to about 0.35 for the four-valve cylinder. Exhaust valves are in general 6 to 11 percent smaller in diameter than the intake valves. The question arises as to what shape of combustion chamber makes possible the application of maximum valve areas. The most favorable conditions appear to be for the case of the spherical-shape combustion chamber with two obliquely arranged valves. Large valves require, however, correspondingly large lifts to which especial attention must be paid, particularly with regard to the durability of the valve springs at the higher valve gear speeds. The smaller lift of the four-valve arrangement is more favorable in this respect, though not providing the possibilities for maximum valve cross section.

In many cases the choice of more favorable valve timing, taking account of the rotational speed and supercharge pressure, leads to a further improvement in the mean effective pressure. From 4 to 8 percent higher values, according to the initial conditions are attainable (reference 4), (fig. 7) and these may be raised still further by an increase in the volumetric efficiency through the scavenging of the burned gases remaining behind (ref. 8).

Undoubtedly, the most effective means for raising the useful pressure lie in increasing the air flow through the cylinder. Care must be taken, however, that the weight of air drawn in is converted into power at high efficiency. According to Ricardo, the effectiveness of a combustion chamber may be expressed by the factor

$$\eta = \frac{\text{indicated power } (hp_i)}{\text{air consumption } (kg/h)} C$$

where C is a constant which for 87 octane aviation gasoline may be set equal to 87.8. According to tests, the spherical combustion chamber has the advantage over the roof-shaped or cylindrical chambers (fig. 8). For operation with direct air intake, high-power mixtures, and well-shaped combustion chambers, there are at present attainable 1,500 indicated horsepower per kilogram air per second (595 bhp./cu. in.). The dependence of this ratio on the supercharge pressure and the fuel-air ratio is shown in figure 9. The effect of the rotational speed is insignificant.

The effect of the compression ratio on the mean pressure is relatively small but on the ignition pressure it is considerable (fig. 10). For a given fuel the mean pressure may be increased more by supercharging than by the application of a higher compression ratio. On the other hand, the higher thermal efficiency of the high-pressure engine leads to lower fuel consumption, so that for purposes of greater economy, range, and power a compromise must be made between the degree of supercharge and the compression ratio, the limits being drawn by the knock rating of the fuel. For an economical ratio between the power and weight of a power plant, Ricardo suggests for the immediate future a rise in the ignition pressure to 80 kg/cm^2 (1,150 lb./sq. in.). With the application of 87 octane fuel, greater compression ratios than 7:1 for the air-cooled engine and 8:1 for the liquid-cooled engine do not appear to be of any further advantage, since beyond this limit the thermal efficiency no longer increases proportionately with the compression ratio ϵ, although the maximum pressure continues to rise. At $\epsilon = 7$ the maximum pressure of 80 kg/cm^2 will be attained at about 1.5 atmospheres supercharge and for $\epsilon = 8$ at about 1.23 atmospheres supercharge.

The effect of the supercharge temperature on the power, according to tests thus far made, is a function of the type of construction of the cylinder. Figure 11 shows that high supercharge pressures may lead to considerable power losses. Here too, possibilities appear for the effective reduction of these losses by the improvement of the supercharger, utilization of the cooling effect of the fuel evaporation, and the lowered atmospheric temperatures at high altitude and, finally, by the cooling of the charge by means of alcohol or water.

With present airplane-engine superchargers there are now attainable adiabatic efficiencies of 70 to 75 percent. Test laboratory results give values lying above 80 percent which will probably be practically utilized in the near future. The importance of improvement in the efficiency may be seen in the fact that a 10 percent increase, for example, in the efficiency of a supercharger with 7,000 meters critical altitude gives an increase in power of 4.5 percent or for equal temperature an increase in the rated altitude by about 1,000 meters. Figure 12 shows the attainable cooling effect through the fuel evaporation as a function of the fuel-air ratio. The temperature of the supercharge air and the efficiency of the fuel preparation determine the proportion of the fuel evaporated. With good atomization approximately half the fuel will evaporate at 20° C. and above 50° C. the total fuel will evaporate. Complete utilization of this advantage will be mainly the result of the fuel and mixture preparation ahead of the cylinders while in the case of direct fuel injection into the cylinder the shorter time available for the mixture preparation will result in a lowered mixture cooling. The utilization of the decreasing air temperature with altitude is possible, however, where the mixture is allowed to form directly in the cylinder or at a position between the supercharger and inlet valve by means of a carburetor and where the supercharge air temperature is already so high on account of the compression that intake air preheating is not required to take care of icing danger or to improve the mixture preparation. At the rated altitude of 4.5 kilometers the difference in power between preheating the intake air to +15° C. and utilization of the cold air already amounts to 8 percent. The most effective mixture cooling through fuel evaporation and elimination of preheating are therefore possesed by engines with pressure carburetors. The possibility of supercharge cooling by means of the addition of water or alcohol will be discussed below in connection with the increase in take-off power.

If the rated altitude of a power plant is 4.5 kilometers about 80 percent of the cruising power will be available at 6 kilometers altitude. These relations will be sufficient, except for some particular cases, for practical purposes in the near future. At 7,000 meters critical altitude of the supercharger, 1.3 atmospheres supercharge are still available at 4.5 kilometers (15,000 ft.) with a supercharge temperature which is still sufficiently far below the knock limit. The required peripheral wheel speed of about 325 meters per second is still far removed from the limiting output of single-stage superchargers, which limit is at present determined by the strong lowering in the supercharger characteristics after attaining the speed of sound corresponding to a peripheral speed of about 500 meters per second and a delivery head of 12,700 meters. Further possibilities for raising the altitude are offered by the improvement of the gas-flow process. Earlier valve opening time and later closing of the outlet valve lead to greater power with increasing altitude through scavenging. A compromise will have to be effected between the valve timing overlap and the present requirements of safe idling and good starting of the engine. In many cases, the determination of the most favorable ignition timing is of importance for the power and fuel consumption at high-altitude operation. From the increase in the air-flow discharge and the decrease in the pumping and exhaust power for a constant supercharge pressure of 1.033 atmospheres and constant supercharge temperature with normal valve timing, the following increases in power with altitude are to be expected:

Altitude in km	0	2	4	6	8
Increase in indicated power in percent	0	4	7	9.25	10.5

The problem of cooling is one of the most serious of the airplane-engine designer. Development and research have given him a wide field and the problems are so numerous that they can be sketched only briefly in the following. Since there is little promise for an appreciable improvement in the present thermal efficiency of about 31 percent, referred to indicated-power and high-power mixture, each increase in the power/displacement ratio leads inevitably to an increase in the heat losses by almost the same percent as the increase in power. Fundamental methods had to be found to conduct away this waste heat in order to obtain moderate temperature rises in the structural elements as cylinder head, piston, and other parts. Thus, for example, Wright has increased the cooling-fin area of the cylinder head and cylinders of the Cyclone by 120 percent while the power has increased by only 62.5 percent (reference 5). In the case of the Pegasus, Bristol has obtained a 113-percent power increase by increasing the total fin area by 164 percent (reference 6). The fin spacing for the cylinder head now amounts to 5 to 5.5 millimeters (.216 in.) for a maximum fin depth of about 40 millimeters (1.56 in.). If, as in the case of the Pegasus XVIII, the cooling fins are milled from the complete cylinder, the fin spacing may be chosen from 4.5 to 5 millimeters and the fin depth up to 55 millimeters (2.16 in.). Table I shows some cooling surface characteristics of airplane engines.

By proper cowling of the cylinder and shaping of the cooling-air inlet, it is possible to lower the cylinder temperatures and cooling losses. Regulation of the cooling-air cross sections at the exit of the engine cowling improves the cooling action at small speeds and at high speeds reduces the cooling which without cross-section regulation would increase with the third power of the flight speed. The cooling-air requirement of present-day engines lies between 15 and 30 kilograms per horsepower-hour (6.83 lb. and 13.66 lb.) and the internal cooling-power expenditure between 1.5 and 3 percent of the engine output. The most difficult cooling conditions occur in climb on account of the high engine power required and the low flight speeds. The high fuel consumption of 300 grams per horsepower-hour in take-off is due to the fact that the insufficient air cooling must be assisted here by the "fuel cooling." Considerable improvement may be expected by the application of forced cooling (reference 7).

By means of liquid cooling, it may be easier to maintain the combustion space and the portion of the cylinder covered by the piston travel at a uniform temperature. The problems here are less those of the engine than those of the radiator since with a liquid-cooled engine it is always possible, on the assumption of sufficient mechanical strength, to attain increased power for special purposes by changing only the amount of fuel, supercharging pressure, and size of radiator. In further development it will again be striven to eliminate the heat stresses of the cylinder and to improve the heat transfer from the external surfaces to the cooling medium and the operating conditions of the piston. According to most recent results obtained, it is possible to reduce the interference drag by lowering the radiator into the fuselage or wing and through the application of nozzle cooling (cooling with small speeds) to reduce greatly the internal cooling drag (reference 7). The wing-surface radiator will lose more and more in importance with the continually decreasing wing areas required for the high speeds. There are, moreover, indications that the profile drag increases on account of the increased viscosity of the heated boundary layer (reference 3). It appears to be possible both for the liquid- and air-cooled engines to attain a cooling power expenditure which makes up only a small portion of the engine propulsive power.

METHODS OF INCREASING TAKE-OFF POWER

The trend of airplane design has been such that the engine is called upon to deliver continually increasing power at take-off. At first a 10-percent-higher-than-rated power was considered satisfactory. At the present time, however, engines are known which have a 25 percent increase of short-period output. Competitive races and performance records also contribute to the ever increasing demand on the engine power. The limit for the supercharge pressure required for these powers is determined by the occurrence of knocking. Fortunately, fuel chemists have succeeded in improving the knock rating of the fuels to such an extent that it is rather the cooling and maximum pressure that may be looked upon as the limits of power increase.

For supercharged engines 87 octane fuel is at present employed almost without exception. Recent tests have shown, for example, that for favorably shaped combustion chambers knocking is set up at a supercharge pressure of 1.4 atmospheres and a supercharge temperature of 110° C. (fig. 11). Such temperatures occur in operation near the ground with a supercharger designed for 4,500 meters rated altitude and 1.3 atmospheres supercharge pressure. In such a case between the rated and the take-off power there would be possible a supercharge-pressure increase of only 7.5 percent. Under the assumption that the maximum mean indicated pressure (p_i = 12.5 atm.) occurs for a gas velocity of 80 meters per second at the intake and for the most usual stroke-bore ratio H:D = 1.1, figure 13 shows the maximum speeds and the attainable powers for the various cylinder sizes. The unfavorable effect of high supercharge temperatures on the engine power here comes plainly into evidence. Investigations having for their object the lowering of the temperature and the raising of the supercharge pressure are concerned with the application of high octane fuels, speed regulation of the supercharger, and supercharger cooling by injection of water or alcohol.

The improved fuel efficiency makes possible the application of higher temperatures, supercharge pressures, and compression ratios without the fear of knocking. The advantages gained in power in raising the octane number from 70 to 87 to 100 are very great. Thus, according to Ricardo, for a compression ratio $\epsilon = 6.5$ in passing from 87 to 100 octane there is an increase in the mean effective pressure by 52 percent if the power in each case is limited by knocking (reference 8). Of this power increase available only about 15 percent is at present utilized. Thus, for example, the 30-liter Pratt & Whitney 14-cylinder double-row radial engine Twin Wasp gives 1,065 horsepower take-off power at 87 octane and 1,215 horsepower at 100 octane. With this fuel the supercharger with no regulation would be utilized better near the ground without lowering of the supercharge temperature and the power required for driving the supercharger. The possibility of raising the compression ratio through the use of high octane fuel up to the maximum compression limit imposed by the engine construction would be a means of lowering the supercharger power requirement and the specific fuel consumption. In addition to the fuels of 100 octane number, there also deserves to be mentioned the favorable characteristics pointed out by O. Kurtz of a three-component mixture Bi-Bo-Alc with 90 octane (reference 4).

In connection with the lowered atmospheric temperature with increasing altitude, the end temperature of the supercharge air for the supercharger with fixed gear ratio and constant efficiency decreases somewhat faster than the intake temperature with the altitude and the required supercharger power increases. As regards the effect of the decreasing exhaust back pressure on the gas flow, there is an increase in engine power with altitude for constant supercharge pressure. In the ideal case of no losses and continuous regulation, the gear ratio between engine and supercharger will be varied so that the presecribed supercharge pressure will just be attained. Power requirement and compression end temperature thereby decrease to such an extent on the ground that for a 4.5 kilometer supercharger and 1.3 atmospheres supercharge pressure, there may be an increase in the take-off power of about 25 percent.

With increasing altitude, the engine power falls off by the increase in the power taken by the supercharger and the end temperature until at 4.5 kilometers rated altitude it reaches the power of the engine with unregulated supercharger. Without supercharger regulation there would be required in the case of the example given an increase to about 1.5 atmosphere for a 25-percent take-off power increase. The advantages of the centrifugal supercharger with speed regulation are maintained not only for the take-off and climb but its application leads to greater rated altitudes such as were not considered possible on account of insufficient take-off power. The question as to what supercharge processes approach the "ideal case" most closely and what speed regulation possibilities possess any promise of success for the airplane engine supercharger was considered by A. Nutt in his paper before the Lilienthal-Gesellschaft in 1936 (reference 5). The two-stage supercharger already in use to some extent may be considered as the first step to speed regulation. According to the favorable results of a test design of the D.V.L. (reference 11), the no-losses, stageless supercharge regulation is no longer to be considered as an unsolved problem. The application of the exhaust turbine supercharger is hindered by the high exhaust temperatures (1,000° C. to 1,150° C.) of internal combustion engines. Their practical application will depend on the further improvement of heat-resisting materials and the production of an economic cooling method of the gases before impinging on the blades without the usual disadvantages for the turbine and the propulsive power, or through sufficient cooling of the endangered structural parts themselves (reference 10). The exhaust turbosupercharger will have the advantage over the mechanically driven supercharger, particularly in fuel consumption and in range at high-altitude flight.

The requirement of effectively lowering the large loss in power at high supercharge temperatures has suggested the utilization of the high heat of evaporation of water and alcohol, since surface radiators, on account of their size and weight, their uneffectiveness in take-off, and their additional propulsive loss in flight are eliminated as far as economical installation is concerned. The results of present D.V.L. tests (reference 4) indicate that through the injection of water or alcohol into the cylinder a considerable lowering in the charging and combustion temperatures amy be attained with small expenditure. Since cooling of the charge appears necessary only for the case of the short-period power output, the weight expenditure for cooling remains within tolerable limits. If the advantages of charge-cooling are combined with the possibilities of a 100 octane fuel, we may obtain power/displacement ratios which with present-day means we shall hardly be able to exceed. The way leads step by step to those peak outputs of 70 to 100 horsepower per liter which can now be attained only in the laboratories on test engines.

On the way to these performances the further development of the two most highly stressed structural parts, namely, the piston and the exhaust valve must lead to special progress. Improvement in the heat flow, sufficient resistance to increased maximum pressures, decrease in carbon deposit, fractures and wear on the piston rings, and, finally, piston cooling are the problems of design and investigation for the near future. Sticking piston rings and piston seizing are the most common of engine disturbances. We can no longer restrict ourselves to the piston rings alone in conducting the heat away to the cylinder walls, but must also, in the view of Ricardo, strive to attain effective cooling of the piston rings by heat transfer to the oil. This requires the use of a very large number of deep cooling fins on the under side of the piston as well as an increase in the distance of the first piston ring from the piston bottom, in order to remove the latter farther from the direct effect of the combustion gases. The lack of uniformity in the quantity and direction of flow of the oil to be injected on the inner side of the piston is to be replaced by a carefully regulated flow of cooling oil and, finally, we may expect improvements also in the piston material.

With the increasing heat to be disposed of by the cylinder and the higher mechanical stresses through the rising rotational speeds, the structural shape and material of the exhaust valve have changed considerably. Chemical cooling of the exhaust valve has been improved by keeping the entire valve head hollow so that it can be cooled in the same manner as the valve stem. Pye announces a new material for the valves which should be an improvement over stellite (reference 9).

THE VARIOUS METHODS OF PREPARATION OF THE FUEL MIXTURE AND THEIR EFFECT ON POWER, ECONOMY, AND SAFETY

The carburetor method still occupies the chief place in mixture preparation before injection. The progress made in power, fuel consumption, and safety are to a large extent the result of the efficiency of our present carburetor installations. Foreign engine manufacturers often guarantee fuel consumptions for cruising of 195 grams per horsepower-hour, and only recently in a test of the Argus As 410 (fig. 4) a fuel consumption of only 186 grams per horsepower-hour could be obtained. Ice and condensation deposits, sensitivity to position, and danger of fire appear as disadvantages of the carburetor for the elimination of which various methods are suggested: carburetor-heating, air-preheating, addition of alcohol, elimination of the float-type carburetor. Ice formation is the most serious problem. After it was found that warming the carburetor by the engine-lubricating oil was inadequate, an attempt was made to warm the intake air by means of the exhaust gases. Space and weight requirements are too great, however, for a sufficiently large preheater and, moreover, preheated air leads to considerable loss in power. A more favorable method, according to the English tests, appears to be the addition to the fuel of 3 to 5 percent alcohol which, whenever there is a tendency to ice formation, is independently supplied by a simple apparatus from a small tank and is atomized together together with the fuel. Pressure carburetors connected between supercharger and cylinder eliminate any necessity for a deicing method and make possible for high altitude operation the utilization of the decreasing atmospheric temperature. With regard to uniform mixture distribution in the case of a large number of cylinders, pressure carburetors offer considerably greater difficulty than suction carburetors arranged ahead of the supercharger. Carefully serviced carburetors at present attain a time interval between overhaulings of 500 to 600 hours.

A fundamental means of elimination of the disadvantages of operation with a carburetor is found in the mechanical preparation and distribution of the fuel. It is known that an engine with fuel injection into the cylinder gives a higher power output than an equally large carburetor engine. The reasons for the increase in power are, according to Ricardo, to be found in the greater air flow due to the elimination of the carburetor throttle losses and in the possibility of the dead air scavenging without loss in fuel. For large overlap of the valve timing an increase of 15 to 20 percent in power may be expected through dead-air scavenging. On the other hand, it is not to be expected that with direct injection merely the fuel preparation will be as good as with the carburetor, but by means of intensive atomization of the fuel adjustment of the fuel jet to the shape of the combustion space and good turbulence of the fuel-air mixture in the cylinder, care must be taken to see that even the last fuel drops reaching the cylinder do not escape combustion.

Under certain conditions, it may even be necessary to make use of the Diesel engine methods to attain an effective mixing. As regards fuel consumption, there is no essential difference between the injection and carburetor engine. The application of high-boiling-point gasoline which, on account of the low volatility cannot be considered for the carburetor engine, is promising for the direct fuel injection into the cylinder.

Of equal importance for all mixture preparation processes is the proper choice of fuel-air ratio and its regulation. Lowering of the fuel consumption is of utmost significance for economy over long ranges. One of the means of attaining it is the operation with excess air. The progress attained in the improvement in the mixture preparation and distribution have made possible the application of higher excess air ratios with lower fuel consumption. The lowest consumptions today lie within the range of an excess air coefficient of 1.10 to 1.25, corresponding to a decrease in power, for constant supercharge pressure, of 10 to 20 percent based on the maximum power mixture ($\lambda = 0.8$ to 0.9, fig. 14). As a result of the lowered combustion speed in the case of excess air, there is a retardation in the pressure rise and the combustion continues far into the expansion stroke with the consequences of after-burning and high exhaust temperatures. By advancing the ignition, these disadvantages may be eliminated and conditions obtained which are suitable for continuous operation. The utilization of this knowledge means a fuel-saving in cruising flight of about 20 percent.

The requirements for increased power, economy, and safety of recent high-performance engines have made it necessary that the pilot be relieved as far as possible from regulating the engine and this function be transferred to regulating devices. The methods of regulating themselves have in the course of development become more numerous and complicated. The power is regulated by the supercharge-pressure regulator operated through oil pressure by changing the throttle-valve setting. In most cases the supercharge-pressure regulators are no longer designed as simple final pressure regulators for a single adjustable maximum pressure but as single or several-stage regulators for variable supercharge pressures. It has the function of always maintaining constant the pressure selected by the pilot's throttle lever and of being continuously variable up to the take-off supercharge pressure so that at all altitudes there remains no range of dead motion of the throttle lever. A similar effect may be attained with a simple final pressure regulator by putting a throttle valve ahead of and behind the supercharger. The application of the excess-air method and flight at high altitudes require, in order to remove the difference in fuel consumption and avoid engine injury due to the inaccurate setting, an independent mixture and ignition-point regulation. The importance of this regulation becomes clear when it is considered that before its introduction differences in fuel consumption of 25 percent were found for the same engine and airplane design. The mixture regulators have in general two fundamental settings, one for full load, denoted as "rich mixture" and one for reduced load, denoted as "poor." Whereas, in the case of the carburetor engine, the mixture regulator only regulates the mixture for altitude in the case of direct-injection engines, the fuel regulator must properly adjust the fuel to the intake air. This explains the fundamental difference in the construction of the two types of regulators.

SPECIAL PROBLEMS

The above considerations have been restricted to the development of the type of airplane-engine construction that is practically the only one in use, namely, the valve-operated, four-stroke, spark-ignition engine. The years of research and development have brought this standard airplane engine to such a high stage of maturity that engines of a newer type of construction may not be expected to surpass its performance in a short time. There are no limits, however, set to the spirit of technical progress and therefore the question arises whether unusual changes in airplane-engine construction might have any chance for success. In the center of these special problems stands the sleeve-valve engine. Interest in the Diesel engine seems in recent years to have fallen off in view of the hardly attainable weight requirement and the continuous decrease in the fuel consumption of the spark-ignition engines. The tendency toward ever-increasing flight speeds further restricts its range of applicability, and only in long-range flight will it remain for the present of advantage over the spark-ignition engine.

The way to sleeve-valve-driven airplane engines was pointed out by Ricardoand the Bristol firm in England. The two engine types, Perseus and Hercules, that are put out in series production are a proof of the practicability of the sleeve-valve engine. The 9-cylinder, radial Perseus XII with 24.8 liters displacement (fig. 15) has a maximum power output of 918 horsepower at 1980 meters altitude and the 14-cylinder, double-row Hercules (fig. 16) with 38.7 liters displacement has an output of 1,375 horsepower at 1,220 meters. These four-stroke sleeve-valve engines already attain the peak values of 36 to 37 horsepower per liter of the poppet-valve engines. The numerous advantages - higher volumetric efficiency, ability to assume a greater load through high knock rating, lower fuel consumption, better mean effective pressures by utilizing stratified charge, and turbulence obtained by Ricardo with Burt-McCollum sleeve-valve mechanism are not to be overlooked. It is not to be supposed that development will stop there.

To the problems of future engine development belongs also that of the two-stroke-cycle engine. For serious attempts seem up the the present to have been made to develop a two-stroke engine for operation with gasoline. The imperfect cylinder scavenging and the difficulty of the heat transfer seriously obstruct the way to success. The straight flow scavenging seems to be the one most closely approaching the ideal case of uncontracted laminar flow and the most successful. The advantage of slots on the cylinder periphery of the opposing piston engine has already been pointed out by O. Kurtz (reference 4). Nothing seems more suitable here than the application of the sleeve-valve already used in the four-stroke engine which is also known to give low head resistance. It is hardly to be supposed that with such sleeve valve gear difficulties will arise in obtaining the proper time areas for the cross section for the scavenging and expansion of the gases. The power expended in scavenging will in this case not exceed 7 to 8 percent of the engine power. In doubling the working strokes, we must take into account the considerable increase in the specific flow heat. For equal mean piston pressures and rotational speeds, two-stroke engines show a 40 to 60 percent higher heat stressing of the cooling surfaces than the four-stroke engines. It is therefore to be assumed that liquid cooling will be the only type of cooling applied to the two-stroke spark-ignition engines for the present, particularly since with four-stroke sleeve engines it is already difficult to cool the cylinder head effectively by air. For the protection of the piston and piston rings against seizing, there are to be used the methods already familiar from the two-stroke Diesel engines and the object will be attained more quickly if it is decided to make use of forced oil-cooling of the piston. The advantages to be expected from the two-stroke engine may briefly be summarized as follows.

Low pressures of the charge due to large scavenging cross sections, lower stressing of engine through the action of the ignition pressures which in each rotation counteract the inertia pressures, and more uniform rotational torque that are all favorable to high speeds with adequate volumetric efficiency and high power to weight ratio; large cylinder outputs that require fewer cylinders or cylinders with smaller displacement volumes as compared with the four-stroke engine; and lower exhaust temperatures that are favorable to the application of the exhaust turbine.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

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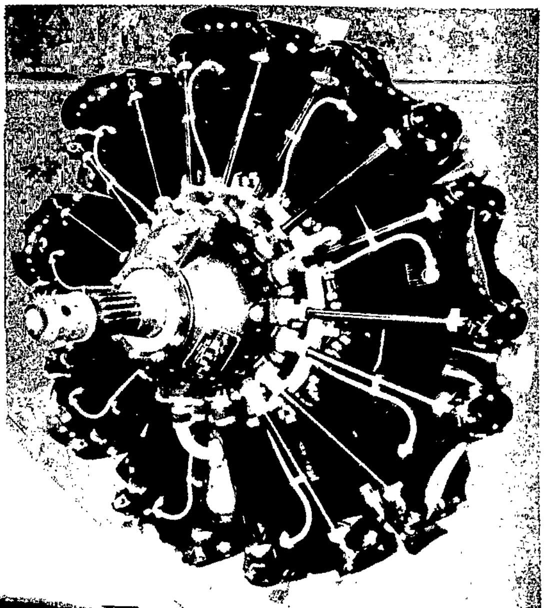
TABLE I

Cooling Area Characteristics of Airplane Engines

	Displacement / Number of cylinders	Take-off power	Cooling area / Displacement			Cooling area / Cylinder power
			Cylinder head	Piston travel	Total	
	liters	hp.	m^2/liter	m^2/ liter	m^2/ liter	m^2/hp.
Wright Cyclone G 100	29.85/ 9	1100	0.435	0.168	0.603	0.0164
Wright Cyclone GR 1820	29.85/ 9	850	.370	.155	.525	.0184
Bristol Pegasus XVIII	29.1 / 9	980	.387	.195	.582	.01725
Bramo Fafnir	26.8 / 9	950	-	-	.661	.0187
BMW 132	27.7 / 9	880	-	-	.602	.0190
Napier Rapier	8.86/16	340	.272	.203	.475	.01235
Argus As 410	12 /12	450	.389	.264	.653	.0175

Figure 1.- Wright "Cyclone G 102". Bore 156 mm, stroke 174 mm, V=29.88 liters, take-off power 1115 hp. n=2300 r.p.m., rated power at 1830 m altitude 913 hp. at 2200 r.p.m. octane number of fuel 90, ϵ = 6.7 , outside diameter 1400m , length 1412 mm ,weight 578 kg, propeller reduction gear 16:11 . Fuel consumption in cruising 193 g/hp.hr. Wright also makes a similar design of a 14 cylinder double row radial engine(V = 42.1 liters) for 1520 hp. take-off and 1217 hp. rated load near the ground.



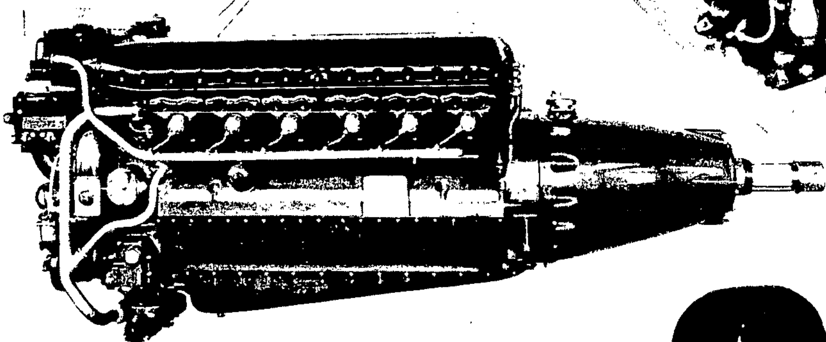


Figure 3.- Allison "V 1710-C 6". 12 cyl., liquid cooled, bore 139.7 mm, stroke 152.4 mm. V = 28 liters , take-off power 1014 hp., n = 2600 r.p.m., 1.205 at. supercharge, cruising power 700 hp., n = 2300 r.p.m., fuel octane number 87 , ϵ = 6 , length 2.4 m. Width 0.778 m , height 1.07 m , propeller reduction gear ratio 2.1 , weight 580 kg.

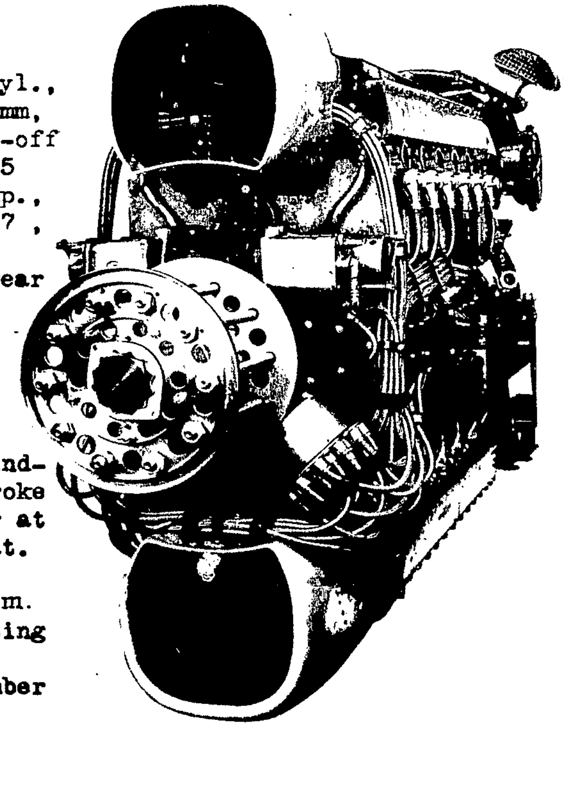


Figure 2.- Napier Dagger VIII. 24 cylinder H type , bore 97 mm, stroke 95 mm, V = 16.85 liters, maximum power at ground 969 hp. at 4200 r.p.m., 1.455 at. supercharge pressure, maximum power at 2.67 km. altitude 1014 hp. at 4200 r.p.m. 1.385 at. supercharge pressure , cruising power (max.) 781 hp. at 3600 r.p.m., 1.279 at. supercharge, fuel octane number 87, ϵ = 7.75 , weight (dry) 592 kg.

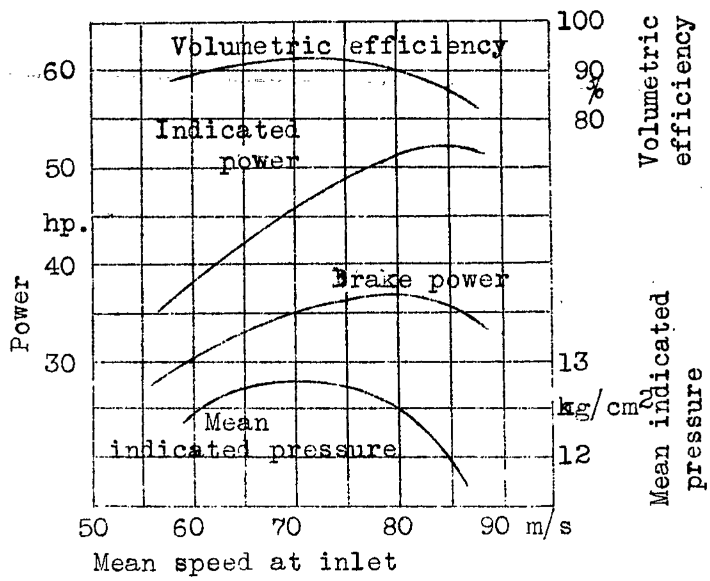


Figure 5. - Power, volumetric efficiency, mean indicated pressure as functions of the velocity at intake. Single-cylinder tests with a 1 liter cylinder, supercharge pressure 1.033 at., ϵ = 6.5, supercharge air temperature t = 20°.

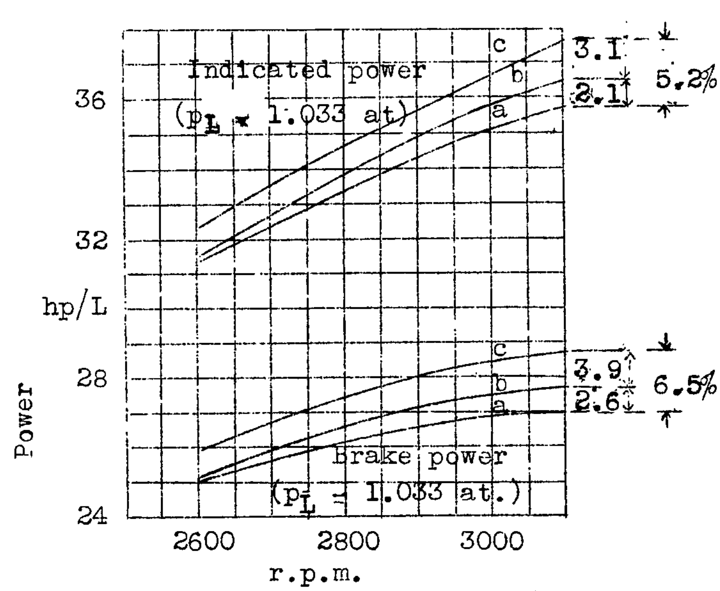


Figure 7.- Increase in power through improved valve timing. a) power curve with outlet cam, b) power curve with more favorable valve timing, c) power curve with more favorable timing and greater opening times of the valves.

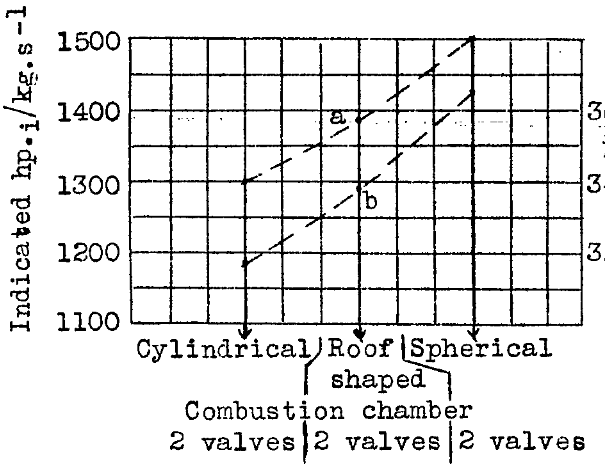


Figure 8.- Efficiency of combustion chambers. a) indicated power per kg. air per second, b) efficiency of the combustion chamber η = indicated power ÷ air consumption (kg/hr) x 87.8, ϵ = 6.5, supercharge pressure 1.033 at. supercharge air temperature 20°, λ = 0.8 - 0.9.

(a) 6 x N_i of single cylinder
(b) Uneven mixture distribution
(c) Flow losses
(d) Auxiliary drive and valve gear
(e) Piston rings
(f) Connecting rod and piston
(g) Crankshaft
(h) Supercharger

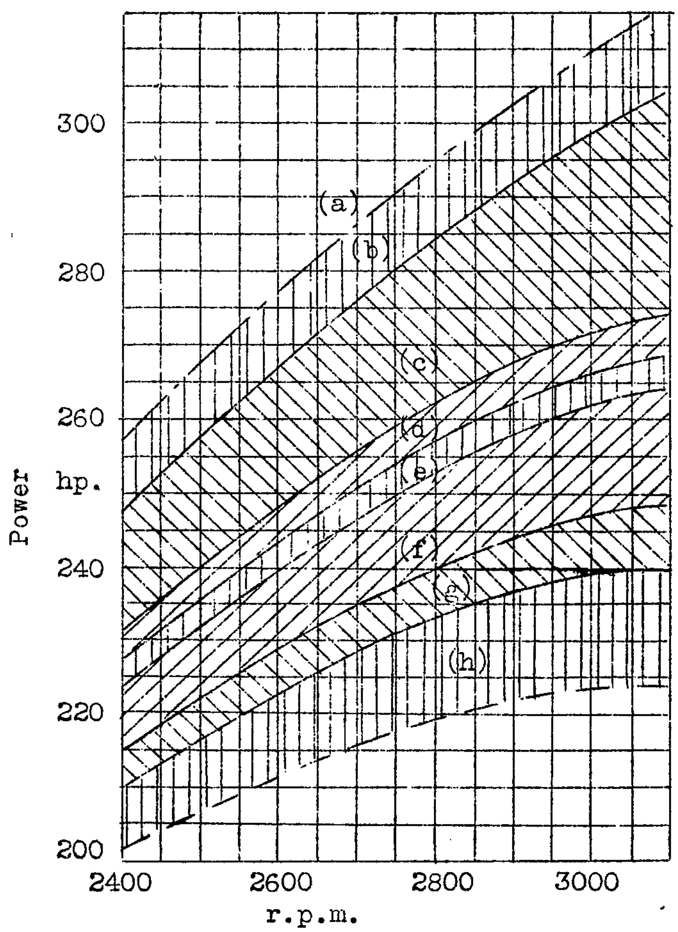


Figure 6.- Internal losses of a six cylinder in-line engine.

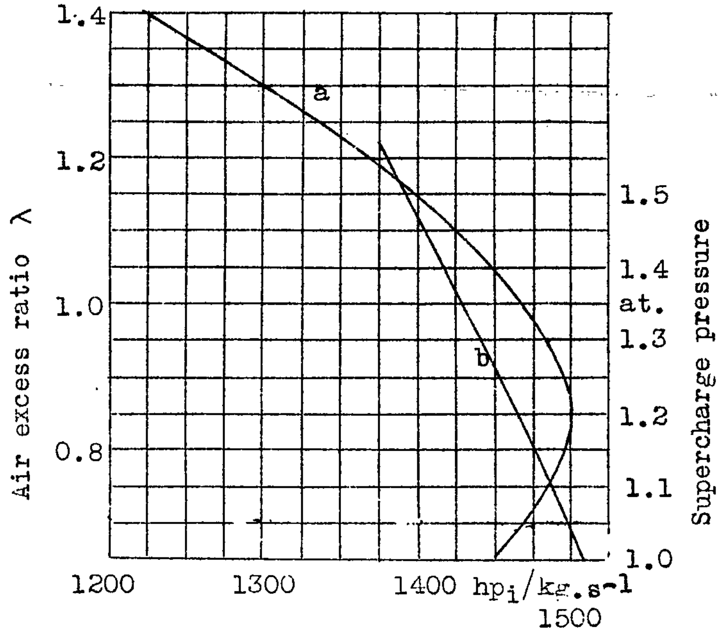


Figure 9.- Indicated horsepower per kg. air per second. a) as a function of the air excess ratio, b) as a function of the supercharge pressure at maximum power mixture (supercharge air temperature 20°, ε = 6.5)

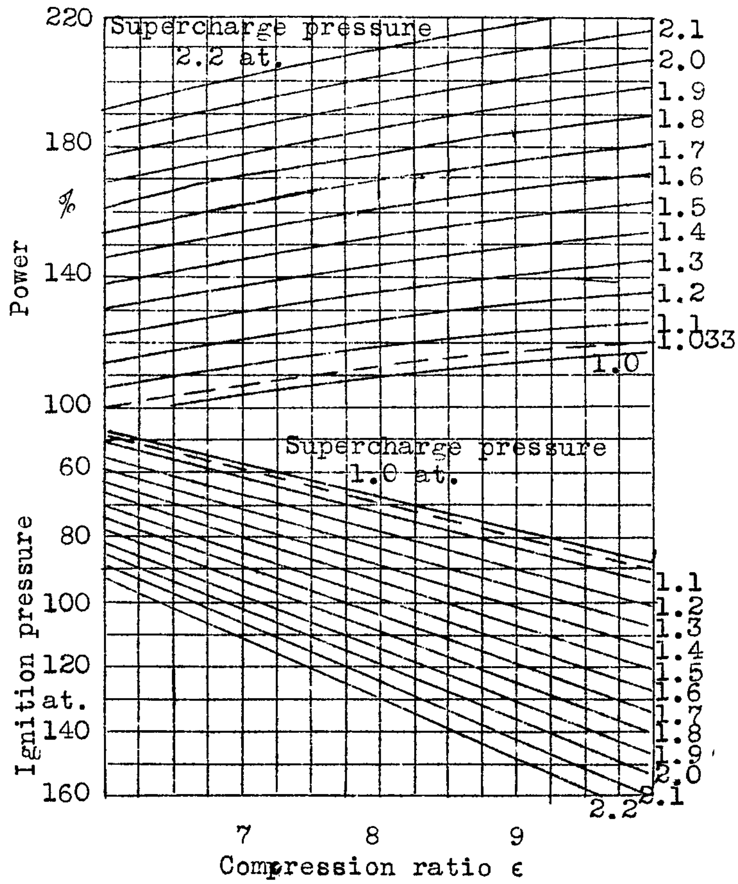


Figure 10. - Power and ignition pressure for various compression ratios and supercharge pressures.

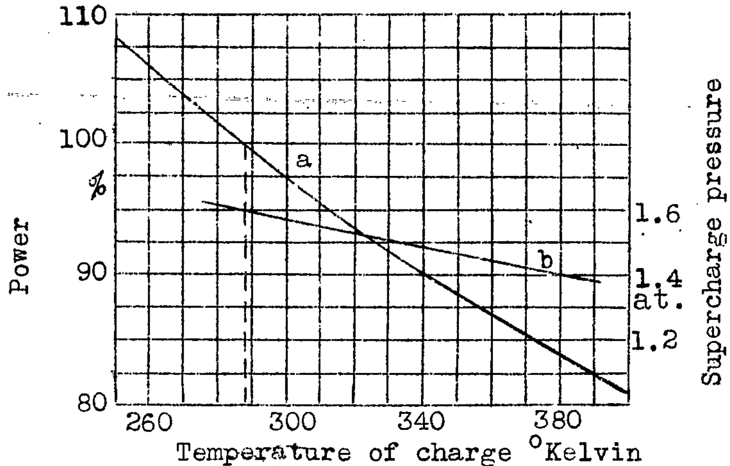


Figure 11.- Effect of supercharge temperature on the power. a) change in power with supercharge air temperature , b) maximum supercharge pressures determined by the knocking limit as a function of the temperature (ϵ = 6.5 , fuel octane number = 87).

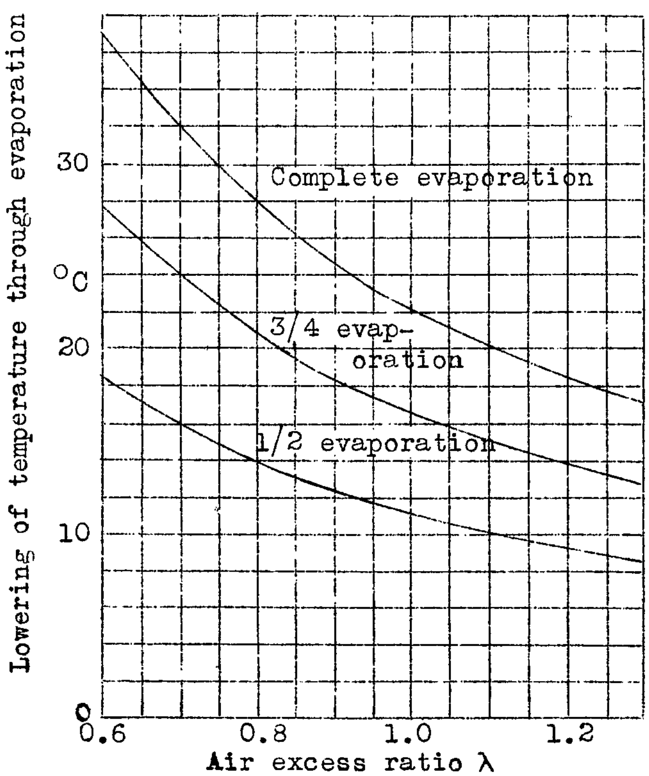


Figure 12.- Effect of fuel evaporation on the supercharge temperature.

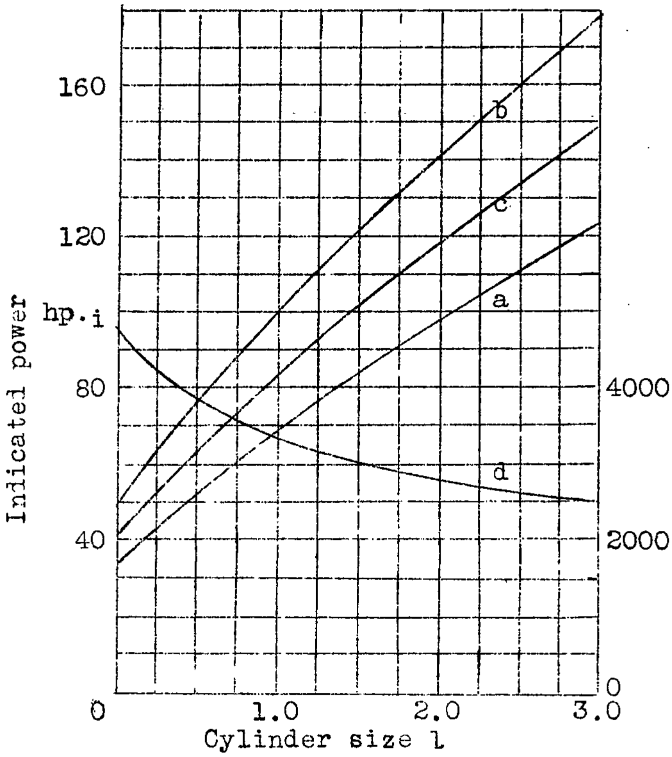


Figure 13.- Cylinder power and speed as a function of the cylinder size. a) maximum indicated power of direct intake engine b) maximum indicated power at 1.4 at. supercharge and 25° intake air temperature c) maximum indicated power at 1.4 at. supercharge and 110° intake air temperature (knock limit), d) maximum rotational speeds. Pm_i = 12,5 at 80 m/s gas velocity at inlet. Stroke - bore ratio H/D = 1.1, inlet area $F_e = 0.1445\ D^2$ $\epsilon = 6.5$, fuel octane number 87.

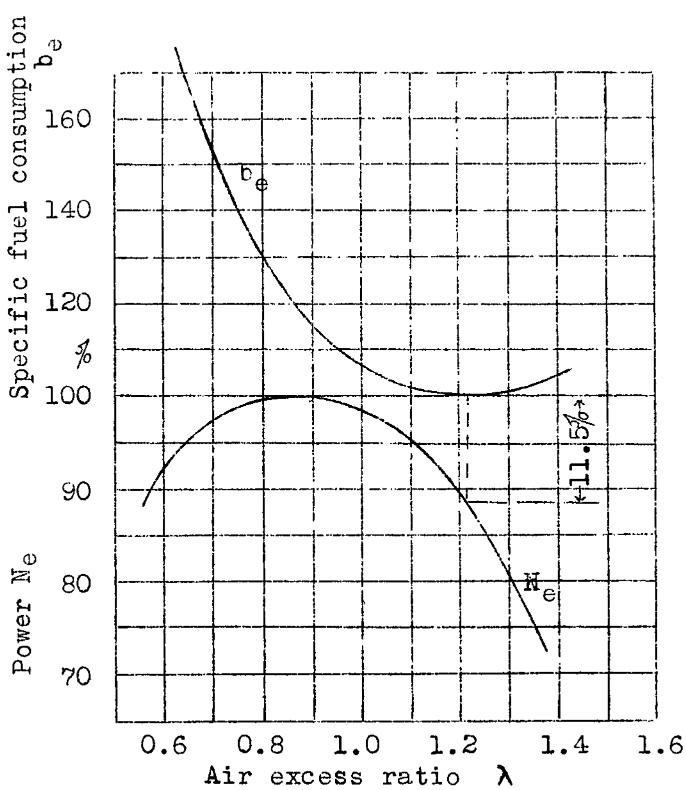


Figure 14.- Effect of excess air on power and fuel consumption.